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Title: **A study of the effect of angular acceptance on material identification for the AHF**

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A study of the effect of angular acceptance on material identification for the AHF.

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Abstract
Data taken with step wedges during experiment 933 show that measurements on a single axis with two lenses can be used to separate nuclear attenuation lengths from radiation lengths in high energy proton radiography. This separation allows proton radiography to provide material identification as well as density determinations. However, the angular acceptance of the AGS set up limited the practical application of this technique to thin objects. A study of the effect of angular acceptance on material identification for the AHF is presented in this report.

Introduction

The lenses used for the AHF drive the cost and performance of the facility in several ways. The chromatic aberrations that contribute to the position resolution depend on the length of the lens system, which in turn drives the length of the transport and cost of the facility. Angular acceptance comes at the cost of lens and transport length, poorer position resolution, and increased cost. Because of these effects this report presents a study of angular acceptance on material identification precision, in order to determine the minimum angular acceptance that does not significantly compromise the Advanced Hydrotest Facility (AHF) performance. The proton momentum is assumed to be 50 GeV/c for this study.

A simple model for proton radiography has been obtained by assuming the nuclear scattering results in the removal of beam particles from the transmitted flux and that Coulomb scattering can approximated by scattering into a Gaussian angular distribution. In this approximation integration of the angular distribution between limits imposed by angle collimators at the Fourier points in the lenses results in closed form expressions for the transmission. A beam transmitted though an object acquires an angular spread,

$$I(\theta) = \frac{1}{\pi\theta_0} e^{\frac{-\theta^2}{2\theta_0^2}}, \tag{1)}$$

Where ,

$$\theta_0 = \frac{14.1}{p\beta} \sum_i \frac{\rho_{Ai}}{X_i}. \tag{2)}$$

Here p is the beam momentum, $\beta = v/c$ where v is the beam velocity and c is the speed of light, X_i is the radiation length for the *i'th* material. Throughout the rest of this work the sum will be implied. This can be integrated between angular limits, θ_1 and θ_2,

$$\int I(\theta)\sin(\theta)d\theta d\phi = (e^{-\frac{\mathrm{X}_2}{\rho_x}} - e^{-\frac{\mathrm{X}_1}{\rho_x}}), \qquad \textbf{3)}$$

where $\rho_x = \sum_i \frac{\rho_{Ai}}{X_i}$ is the areal density of an object, $\mathrm{X}_1 = \frac{p^2\theta_1^2}{2\times 14.1^2}$, is a characteristic areal density associated with the large polar angle limit, θ_1, and, $\mathrm{X}_2 = \frac{p^2\theta_2^2}{2\times 14.1^2}$, is a characteristic areal density associated with the small polar angle limit, θ_2.

Multiple lenses on a single axis, with different angular collimators, allow Coulomb radiation lengths to be separated from nuclear attenuation lengths in proton radiography. The attenuation due to nuclear scattering is exponential with a length, λ. Transmission through a single lens is given by,

$$T = e^{-\rho_\lambda}(e^{-\frac{\mathrm{X}_2}{\rho_x}} - e^{-\frac{\mathrm{X}_1}{\rho_x}}). \qquad \textbf{4)}$$

Data from two lens with different collimators can be used to separately measure ρ_λ and ρ_x. The ratio of these, MID=$\rho_x/\rho_\lambda = X_0/\lambda$, is independent of density and is a constant that depends on the material. We call this the material identification parameter, MID, and use it to quantify the accuracy with which material can be identified in proton radiography.

Analysis

In a previous report we have presented an analytic error analysis and have shown the best collimator configuration for extracting this information is a large collimator in the first lens and a beam blocker or Ferm collimator in the second lens, and we present data from line C to support this conclusion[1]. In that analysis simplifying assumptions about lens acceptance were made in order to obtained closed form expressions for the error analysis. In the current report we perform a Monte Carlo analysis aimed at determining the optimum angle cuts for a 50 GeV lens for the AHF that allows a consideration of smaller angular acceptance in the first lens.

Equation 4 has been incorporated into a model to calculated transmission through a step wedge for a two-lens system. The steps spanned the range of 50 gm/cm^2 to 500 gm/cm^2 and the material was chosen to be U^{238}. Statistical fluctuations in the transmitted flux were modeled using a normal distribution appropriate to a fixed incident flux. A sample of the results for the transmitted flux for the first and second image plane is shown in figure 1). The incident flux was taken to be 10^6 per pixel and the incident momentum was assumed to be 50 GeV/c.

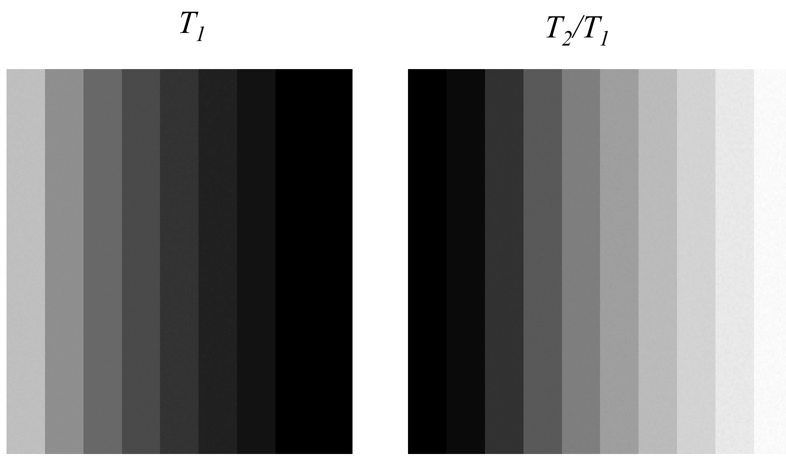

Figure 1) Images of the transmitted flux through a Uranium step wedge. The incident flux was taken to be 10^6 per pixel. The first lens had an angle cut of 10 mrad and the second a Ferm collimator blocking angles below 3 mrad.

Equation 4) can be inverted using data such as that presented in figure 1) to obtain images of radiation length weighed and attenuation length weighted densities. We solve this problem by set it up as a least squares minimization and used a caned IMSL routine to provide the solution. The material identification parameter is calculated by computing the ratio, and the statistical fluctuation level can be calculated as a relative measure of different aperture configurations. Figure 2) shows the images obtained from the data presented in figure one obtained from this procedure.

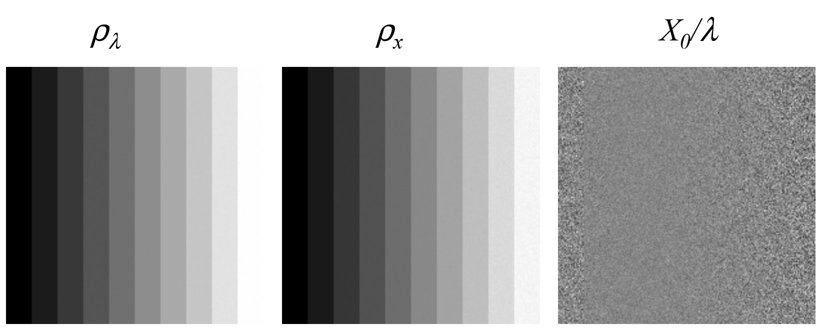

Figure 2) results of the analysis outlined in the text. The material identification parameter, presented on the right, is seen to be independent of material thickness. The fluctuation level can be observed to vary with thickness.

We have performed a sequence of such calculations with the first lens aperture fixed at 100 mrad, while varying the aperture in the second lens in order to find the optimum aperture in the second lens. For each calculation the factional RMS fluctuation level in the MID parameter is plotted as a function of thickness in figure 3).

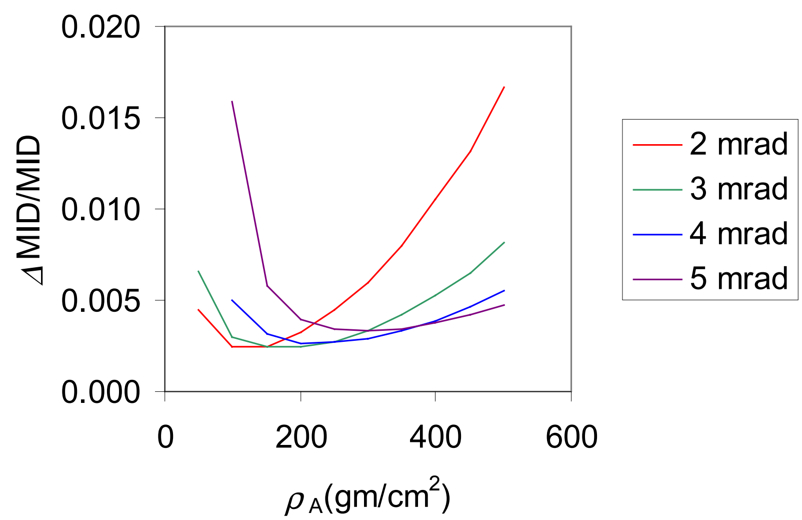

Figure 3) Flucation level in the MID as a function of thickness for different angle cuts in the second lens. These calculations follow the analytical expectations present in reference 1).

Based on the data shown in figure 3) we have calculated the statistical precision of the calculated MID as a function of the aperture in the first lens; the minimum angular acceptance for the lens system. These results are shown below in figure 4).

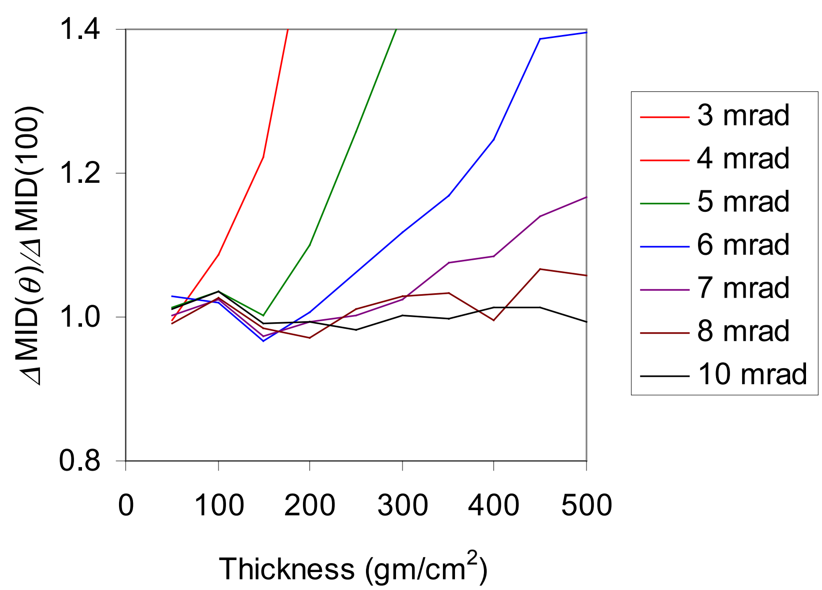

Figure 4) Ratio of the flucuation level in the MID parameter for a given angulate acceptance to that obtained wirh 100 mrad as a function of thickness.

The data are displayed as a ratio of ΔMID for a given angular acceptance to that obtained with a 100 mrad cut in lens 1 to emphasize the degradation due to the angle cut. Based on this plot one can conclude that for AHF radiography a 7 mrad angle cut provide reasonable performace across the entire thickness range presented in the above analysis.

Summary

Then statistics of the transport of 50 GeV/c protons through a uranium step wedge and various lens systems has been modeled to determine the minimum angular acceptance that does not compromise AHF performance. The statistical fluctuation level in the MID parameter has been chosen as a suitable metric of performance. Based in this study it has been determined that 7 mrad provided acceptable performance of the range of thickness which will be radiographed at the AHF.

[1] C. L. Morris, Eric Ferm, Nick King, Mary Hockaday, Gary Hogan, Kevin Morley, Alexander Saunders, and John Zumbro, "A comparison of collimators and anti-collimators for multiple scattering radiographphy," LAURxxxx, 1999.